DEVELOPMENT OF THE FACET CRYOSTAT

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ABSTRACT

A "proof of concept" prototype cryostat has been developed to demonstrate the ability to accommodate low temperature science investigations within the constraints of the Hitchhiker siderail carrier on the Space Shuttle. The Fast Alternative Cryogenic Experiment Testbed (FACET) hybrid Solid Neon - Superfluid Helium cryostat has been designed to accommodate instruments of 16.5 cm diameter and 30 cm length. In this paper the design requirements, the implementation experiences and test results will be discussed.

INTRODUCTION

The start of the build era for the International Space Station (ISS) has resulted in the end of regularly scheduled microgravity science opportunities such as the United States Microgravity Payload (USMP) missions on which the Lambda Point Experiment (LPE) and Confined Helium Experiment (CHeX) were performed. In addition, the ISS is not scheduled to be completed enough for the planned Low Temperature Microgravity Physics Facility (LTMPF) to conduct experiments until 2003 at the earliest. This situation creates a backlog of selected low temperature flight definition experiments. It also compromises the ability to conduct any incremental tests of scientific or technological concepts in microgravity until after the start of the Space Station era.

To address this gap in manifest opportunities, several approaches were investigated, alternate carriers for the existing Low Temperature Platform (LTP) cryostat[1], an early flight of the LTMPF, and FACET. The mass and volume of the LTP and LTMPF constrain these platforms to cross bay carriers that are not in the baseline shuttle manifest. In the case of an ISS schedule slip, the carriers most likely to be manifested are pressurized modules, such as SPACELAB, which are not compatible with crossbay carriers. Also, an earlier flight of the planned LTMPF requires an accelerated funding schedule for early completion of that facility.

The Fast Alternative Cryogenic Experiment Testbed (FACET) project was a one year proof of concept study to demonstrate, through the design, construction, and test of a prototype, the feasibility of flying cryogenic payloads aboard the Space Transportation System (STS) (a.k.a. the space shuttle) during the ISS build era. This paper describes the development of the cryostat. The remainder of the payload and its development is described elsewhere[2]. This paper will describe the objectives, requirements, and constraints for the cryostat and its development, the design approach, and the results of the prototype hardware development.

OBJECTIVES AND REQUIREMENTS

The ultimate objective of the FACET project is to produce a simple, low cost, facility providing frequent flight opportunities before the availability of the Low Temperature Microgravity Physics Facility (LTMPF) for existing flight definition Principal Investigators. The prototype was to demonstrate, within tight schedule and cost constraints, the feasibility of a flight system by the test of ground hardware of which the technical approach could be used to develop low cost flight hardware. It was desired that the flight system should be compatible with multiple reflights, each capable of supporting a different investigation.

Table 1 Cryostat Performance Requirements

Parameter	Requirement
On Orbit Lifetime†	≥ 6 days
Bath Temperature	< 2.17 K
Instrument Volume	> 4.7 Liters

† Predicted flight system performance after first launch opportunity

In this development, cost and schedule were the driving constraints, with technical scope and performance secondary. The performance requirements, shown in Table 1, were derived from minimum mission requirements negotiated with the backlogged science investigators or their representatives. Among the features considered, but not included in the prototype due to the development constraints, were porous plug phase separators, and motor driven cold valves.

Early in the development, a carrier trade study identified the Hitchhiker Siderail (HH-S) carrier as having the optimal mass, volume, telemetry, ease of integration and manifesting opportunities consistent with the needs of the low temperature microgravity fundamental physics program. Hitchhiker siderail carrier payloads have flown an average of four times a year. They have flown with a multitude of other payloads, including a TDRSS satellite deployment, MIR servicing missions, SPACELAB missions and the USMP missions. During the station build era, the hitchhiker office has an agreement to fly on a "mass available" basis. In fact, several Hitchhiker Siderail payloads flew during the mission which deployed the first US module of the ISS, the Unity module, and the first servicing mission.

Baselining the Hitchhiker Siderail (HH-S) as the carrier, placed challenging constraints on the design[3]. The body of the cryostat needed to fit within an envelope 0.64 X 0.64 X 0.99 m. The total mass, including siderail mounting hardware, had to be less than 880 kg. The fundamental structural frequency of the cryostat had to exceed 35 Hz.

Baselining the Hitchhiker Siderail (HH-S) as the carrier also placed operational constraints on the design. Probably the most design driving constraint is the ability of the cryostat to safely operate unattended for at least 65 hours, but as long as 161 hours (for a 96 hour launch window), before launch. In addition, the Hitchhiker Siderail (HH-S) carrier does not have "T0" power during the aforementioned 65 - 161 hour period, precluding the use of a vacuum pump to keep the helium within the cryostat superfluid as was done with the LTP. The orientation of the cryostat during servicing on the launch pad was also dictated by the choice of carrier.

DESIGN APPROACH

In early feasibility analyses, it was decided that, given the volume constraints, and the conducted heat load from the electrical leads and plumbing associated with a typical low temperature microgravity fundamental physics instrument, it was unlikely that a cryostat that relied on liquid helium alone would meet the lifetime requirements. Therefore a hybrid approach was chosen.

Although cryocoolers were initially considered for interception of the conducted heat loads to the helium due to the instrument, there were eventually abandoned due to concerns over induced vibration, and the size of the radiators required to reject the waste heat.

Instead, solid Neon was chosen as a "guard" cryogen for a variety of reasons. The temperature of solid Neon ($\leq$ 24K) is much lower than that of the more commonly used cryogen Nitrogen (65 K). The radiation heat load on the Helium reservoir is thus nearly 2 orders of magnitude smaller. Solid neon has an appreciable heat of sublimation (~ 105 Joule/gm). Solid neon is very dense (1.444gm/cc) and will therefore not occupy too much space. The stresses created during solidification from the liquid state do not deform typical metal tanks. In addition, neon is much safer than hydrogen.

Another alternative considered, but ultimately abandoned, was the concept of designing a cryostat to operate *within* a Get Away Special (GAS) can. Ultimately, the volume and mass constraints proved too restrictive for the performance objectives. Instead, the design is to make the vacuum shell identical to the GAS can. This allows direct mounting of the cryostat to the siderail using existing, flight qualified, hardware. In turn, we then imposed the same requirements on the interior elements of the cryostat that are levied on GAS payloads[3].

Throughout the design phase, projections of performance were accomplished with the aid of a self consistent spreadsheet model[4]. The model solves for the temperatures of 6 nodes assuming values for the outer shell, neon reservoir, and helium reservoir temperatures. The model also included vapor cooling, when appropriate, using the product of the vapor specific heat and the temperatures of adjacent shields. The model is iterated until the node temperatures "relax" consistent with the temperature dependent thermal links.

The thermal model results indicated that without sufficient helium boiloff, it would be impossible to keep the neon from partially melting between last servicing and launch, even if the neon was cooled to below 10K at the last servicing.

Moreover, the thermal analysis also indicated, that due principally to the small thermal mass of helium within the cryostat, it would be impractical to rely on thermal stratification to provide sufficient boiloff while maintaining some helium in a superfluid state between the last servicing and launch[5].

However, thermal modelling did indicate that even with the nominally 40% loss of helium volume pumping down from 4.2 K to below 2 K, the on orbit lifetime requirements could be met if the heat load to the helium during on orbit operations was significantly less than during the period between last servicing and launch. Therefore the baseline operating scenario chosen was, during the time between last servicing and launch, to have the helium vent at its normal boiling point, and the neon to be held, subatmospheric, below its triple point. Once on orbit, the neon would begin sublimating to the vacuum of space, and the helium would be pumped superfluid via a phase separator of the type developed for SHOOT[6], which would be fed by Liquid Acquisition Devices (LADs)[7], before switching over to steady state operation with phase separation via a "standard" sintered stainless steel porous plug. The helium boiloff rate during the time between last servicing and launch would be maintained with a small battery powered heater, which once on orbit, would be turned off, decreasing the heat load to the helium.

The thermal model results also aided in the optimization of on orbit lifetime via the relative sizing of the helium and neon reservoir volumes. Estimates of the helium boiloff necessary to keep the neon frozen during the time between last servicing and launch, estimates of the efficiency of pump down from normal to superfluid, and estimates of the heat loads during steady state on orbit operation eventually lead to a choice of a helium reservoir nearly half again as voluminous as the neon reservoir.

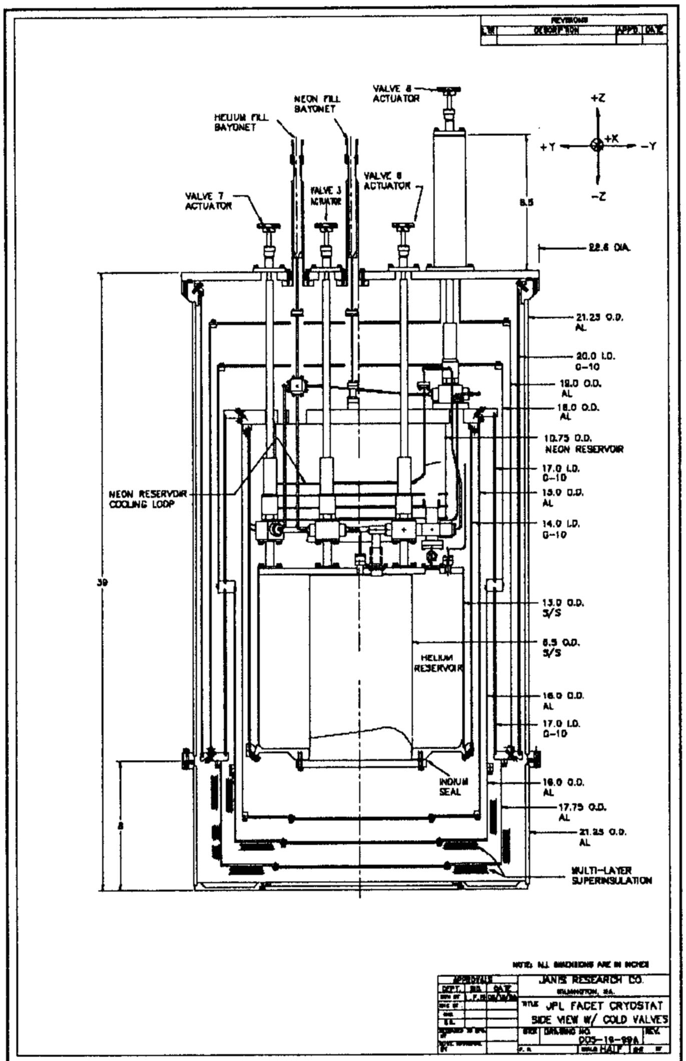

Figure 1 Cross section of FACET cryostat

CRYOSTAT DESIGN

A cross section of the FACET cryostat is shown in shown in Figure 1. The cryostat is a hybrid solid neon - liquid helium with "folded tube" G-10 supports. There exist field joints in all vapor cooled shields at the same axial location as the cold flange joint to aid in instrument integration. The shield closure plates and warm flange (collar) interface are modular to accommodate a wide variety of instrument input/output. The instrument cavity has an interior diameter of 16.51 cm and a depth of 30.48 cm. The instrument cavity has a vacuum independent of the cryostat vacuum when sealed with the instrument cold flange (and pumped through an instrument provided instrument guard vacuum vent). The instrument cavity is surrounded by an annular 15 liter (+ 2 liter ullage volume) liquid helium reservoir. Heat transfer from the instrument to the helium is accomplished via conduction through the (annular) reservoir's walls (i.e., the instrument is in a "dry well"). Axially displaced from the helium reservoir is the 9.5 liter (+ 1.5 liter ullage volume) solid neon reservoir. Anchored within the solid neon reservoir is an aluminum foam[8] to aid in heat transport within the neon. The cryogen tanks, as well as the rest of the cryostat internal elements, are structurally, as well as thermally separated by "folded tube" G-10 supports. There are two vapor cooled shields, in addition to the shield attached to the neon reservoir. There exist field joints in all vapor cooled shields at the same axial location as the instrument cavity cold flange joint to aid in integration. The shield closure plates and warm flange (collar) interface (not shown) are modular to accommodate a wide variety of instrument input/output. The prototype was built with two vent lines from the helium reservoir, one for each of the type of phase separators that would be necessary for a flight version of the cryostat. The vent lines from the solid neon reservoir, as well as from the helium reservoir, were anchored to the vapor cooled shields.

The valving of the interior cryostat manifold allows for the precooling of the lines and vapor cooled shields before topping off the helium, thus avoiding undesired increases in instrument temperature. A bypass in the helium cryogen manifold creates a cooling loop for solidifying the neon. For the prototype, the neon was solidified after filling the reservoir with liquid at its normal boiling point. Due to tight schedule and cost constraints, the cryogenic valves used for the helium manifold in the prototype cryostat were manually actuated. For a flight cryostat, stepper-motor actuated valves similar to the ones used on SHOOT[9] would be used. Determining the feasibility of the flight design to meet on orbit lifetime objectives from prototype's demonstrated lifetime thus involves taking into account the difference in heat load due to the cryovalves for the prototype and for the flight design. In the prototype, the majority of the heat leak due to the cryovalves is from the radiated heat leak around the valve actuators. In the flight design, the majority of the heat leak due to the cryovalves is from the conducted lead resistance, and is much less than the radiated heat leak in the prototype. The thermal model was used to select the number of layers of multi-layer insulation[10] so that radiation was comparable in heat leak to other sources. The cryostat has Germanium Resistance Thermometers and Silicon Diode thermometers throughtout for the monitoring of housekeeping data. The pressure within the helium and neon reservoirs is also monitored. A heater for mass gauging, as well as a commercial superconducting transition level gauges were installed in the helium reservoir. The as built prototype has a dry weight (excluding vacuum shell) of 82 kg. This is 6 kg below the requirement, including the allocated mass for cryogens (8.6 kg), instrument (15kg) and external manifold (1.8 kg). The prototype design provides for 5.6 liters of instrument volume, exceeding the requirement by 19%. A finite element analysis of the design using NASTRAN was performed. The lowest lowest natural frequency (lateral mode) of the internal cryostat structure, at 48 Hz, is greater than the 35 Hz requirement, and close to the goal of 50 Hz.

TEST AND ANALYSIS

Projections for the performance of a flight cryostat are achieved using a numerical model that reproduces the performance of the ground prototype. All radiative and conductive heat flow path resistances are temperature dependent. Heat flow through MLI was modelled using the empirical formula[10] and a conservative loft of 24 layers/cm . The effect of MLI penetrations were included by adding a 1/4 inch perimeter of blackbody coupling to adjacent shields around each penetration and field (assembly) joint. The emissivity on the LHe & SNe cooled surfaces (a single layer of aluminized mylar) was taken at a conservative 0.03.

In this conservative model, the radiated heat loads due to nearly unavoidable imperfections at the penetrations in the MLI are nearly an order of magnitude larger than the heat loads through the rest of the blanket on both the OVCS & IVCS. We note that in the thermal model developed during the CHeX project for a conventional helium dewar[11], the dominant heat load (by nearly two orders of magnitude) to the helium reservoir was conduction along the supports. By the incorporation of a solid neon reservoir, the dominant heat load to the helium reservoir becomes "stray radiation". Although controlling radiation leaks to the helium reservoir will ultimately extend the total lifetime of the cryostat, it may become necessary to incorporate the activation of a heater during the launch hold to ensure adequate vapor cooling.

Measurements of ground performance during simulated on orbit operation agreed well with numerical modelling of the cryostat. The model predicted temperatures and heat flow data inside the prototype cryostat during simulated on orbit operation are shown in Figure 2. The numbers in parenthesis are the actual data from simulated operation. Note that the heat flow into the helium tank is dominated by radiation of 36 mW (from leaks around the cold valve actuators). On orbit, vapor cooling from both the solid neon and the liquid helium can be used. With the addition of Neon vapor cooling, the on orbit heat load to the neon is less than half of heat load to the neon during the launch hold.

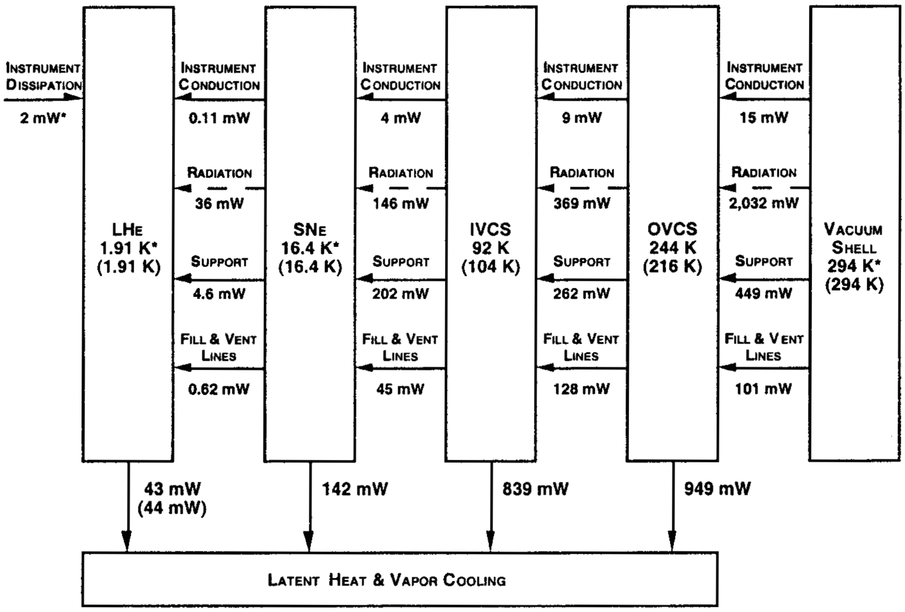

Figure 2 Steady State Model Predictions. Prototype test data are given in parenthesis. Model inputs are marked with an asterisk (*).

In addition, the model has been used to estimate the "heater power" necessary to keep the neon solid during the launch hold (It's ~49 mW for a total of ~ 58.5 mW). We have also determined the efficiency of the conversion from normal to superfluid in the test to be ~57%. From these numbers and the temperature dependent latent heat of helium we calculated the estimated lifetimes.

To predict the on orbit performance of a flight cryostat, first the decreased temperature of the outer shell needs to be taken into consideration. In the cargo bay of the space shuttle, the vacuum shell of the cryostat drops to temperatures (which vary depending on orbiter attitude) around the freezing point of water (based on data from the LPE and CHeX missions). Secondly, the proposed flight cryostat would utilize the commercial off the shelf (COTS), flight qualified, stepper motor driven cryovalves for the internal cryostat manifold. These valves were first used on SHOOT and have subsequently been successfully used in many other space qualified cryostats. Without the 36 mW of "stray" radiation to the helium reservoir, the total heat load to the neon increases, but the helium lifetime increases dramatically. Without the stray radiation, the principal heat loads to the helium reservoir consists of two sources: conduction through the structure from the neon reservoir, and internal dissipation due to the operation of the instrument (see Figure 3). In this scenario the cryostat lifetime is limited by the neon reservoir. Since the heat load to the neon reservoir in this scenario is more than double the heat load in the ground simulation, the neon lifetime would "decrease" to 15 days. With an order of magnitude less heat load to the helium than in the prototype cryostat, orbit helium lifetime could have been as long as 21 days.

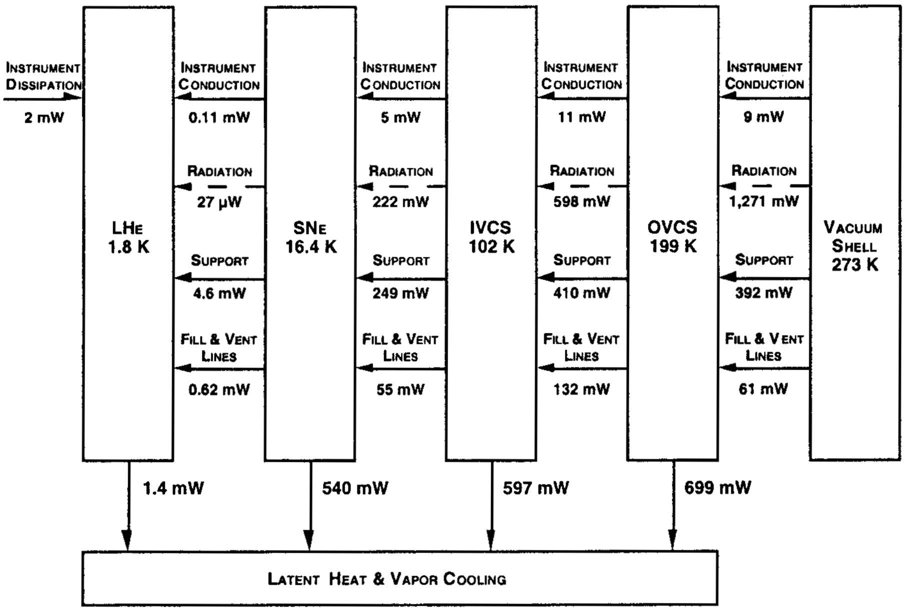

Figure 3 Predicted steady state heat flows for a flight FACET cryostat

The result is that the predicted helium lifetime, for the proposed flight cryostat, depending on whether the launch is at first (65 hours) or last (161 hours) opportunity, is 29.5 or 6.5 days (respectively).

We therefore conclude that it would seem more than feasible, with mechanisms in place to assure adequate helium vapor cooling on the launch pad, and to minimize radiation heat loads to the helium reservoir, to construct a flight cryostat that could provide liquid helium cooling to a science instrument for the full duration of even the longest shuttle missions (16 days).

SUMMARY

The development of the FACET prototype cryostat has proven the feasibility of a multi-use, simple, low cost, facility to accommodate low temperature cryogenic payloads within the constraints of the Hitchhiker siderail carrier on the Space Shuttle. Such a facility could provide frequent flight opportunities during the build era for the International Space Station.

All requirements (performance, hitchhiker payload and development constraints) were met or exceeded. Test data from the prototype indicate that flight cryostat that could provide superfluid liquid helium cooling to an instrument for the full duration of even the longest shuttle missions (16 days).

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